A Milwaukee Model for LID Hydrologic Analysis

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ABSTRACT

In 2002, the Milwaukee Metropolitan Sewerage District (MMSD) began to explore the potential for Low-Impact Development (LID) techniques to help development projects meet the District's storm water management regulations. One general concern associated with using LID was the apparent complexity of determining the cumulative hydrologic effect of relatively small, interconnected LID components such as green roofs, bioretention cells, permeable pavements, etc.

An adaptation of the Natural Resources Conservation Service (NRCS) unit hydrograph method was developed to provide an approach to the LID hydrologic analysis that remained relatively simple. This adaptation aggregates the LID retention volume across the site and treats that volume explicitly as a depth of runoff (i.e., excess rainfall) that must be exceeded before the convolution calculations generate a positive value for the runoff hydrograph. For practical purposes, this approach compared favorably against other alternatives, such as adjusting the composite NRCS curve number for the site, or treating all the retention volume as if it were an in-line storage volume situated immediately above the drainage area outlet.

Calculations for the preferred approach have been formulated in a spreadsheet that allows the user to input the amount of retention provided by each of several kinds of LID components, and then see immediately a recalculated hydrograph that reflects the predicted effect of the aggregate retention volume. The spreadsheet, which has been dubbed the "LID Quicksheet", is expected to be incorporated along with its documentation into the MMSD stormwater management guidance.

INTRODUCTION

The Milwaukee Metropolitan Sewerage District (MMSD) has establishhd a set of stormwater management requirements pertaining to development or redevelopment projects that cause an increase in the impervious surface area of 1/2 acre or more. (MMSD 2002a) Communities have considerable flexibility in choosing how to comply with the new requirements (MMSD 2002b).

Communities that approve of a site-specific approach can submit stormwater management plans that demonstrate compliance with Unit Release Rate (URR) requirements. This means that peak flows should not exceed 0.50 and 0.15 cubic feet per second per acre for the 1% and 50% annual exceedance probability storms, respectively.

An optional set of requirements is associated with what is called the Volumetric Design Procedure (VDP). VDP requirements can be met when the volume of runoff generated during a critical period within the design storm does not exceed the corresponding predevelopment volume. The critical period generally corresponds to a period of high flow in main channel of the watershed in which a site is located. Critical periods for major watersheds in the District have been predetermined.

This paper describes technical considerations associated with a software tool that was developed so that stormwater engineers and plan reviewers might, without excessive effort, establish the degree to which a low-impact development approach would satisfy the URR or VDP requirements for a given site.

METHODOLOGY

As the effort to find or develop an appropriate technical approach initially got underway, stormwater engineers within the MMSD service area were already submitting stormwater management plans that applied conventional NRCS methods for calculating runoff peaks, volumes and hydrographs, as in TR-20 (NRCS, 1984). Since the use of NRCS methods was a matter of standard practice, an adaptation of these methods to incorporate LID design was generally favored over an entirely new approach. Several adaptations were explored.

The familiar NRCS runoff depth formula, as given in TR-20, is

$$Q = \frac{\left(P - I_a\right)^2}{\left(P - I_a\right) + S} \tag{1a}$$

where Q = runoff depth
P = precipitation depth
S = potential maximum retention after runoff begins
I_a = initial abstraction, volume that must be filled before runoff begins

Additionally, S is related to the NRCS curve number CN, which reflects soil conditions land use, and antecedent moisture conditions, as

$$S = \frac{1000}{CN} - 10. \tag{1b}$$

The standard method for generating a runoff hydrograph using the SCS unit hydrograph with convolution calculations involves the following steps for each time increment:

1. Within the storm event, calculate the total rainfall up to that point in time.
2. Check the total rainfall against the capacity that needs to be filled on the land surface (the initial abstraction) before runoff can occur. That is, determine whether P has become greater than I_a.
3. If the total rainfall has exceeded the initial abstraction, calculate the total runoff depth (i.e., excess rainfall) using Equations 1a and 1b.
4. Calculate the incremental increase in runoff depth associated with the time step.
5. Construct a hydrograph that represents the outflow generated by the single increment of runoff volume, based on the unit hydrograph for that drainage area.
6. Repeat for each time step within the storm, producing a component hydrograph associated with the runoff increment for each time step.
7. Add the component hydrographs to establish a total storm hydrograph for runoff at the outlet.

This basic algorithm was incorporated into a spreadsheet so that modifications to the calculations could be readily tested.

Five options based on the NRCS unit hydrograph calculations were compared. Two of the options perform calculations directly on the unadjusted runoff hydrograph that is created using the standard NRCS approach. For those two options, retention is accounted for after the total storm hydrograph is established, i.e., after Step 7 above. The remaining three options execute different modifications of the NRCS runoff depth formula. In each of those three options options, retention is accounted forin the depth calculations before a hydrograph is generated, i.e., before Step 5 above.

Option 1. Truncate the runoff hydrograph

One approach to evaluating the impact of on-site retention on a drainage area is to calculate the runoff hydrograph normally and then truncate the runoff hydrograph (Prince George's County, 1999). This method is equivalent to treating all the storage as if it is situated at the drainage area outlet. The rate of runoff is assumed to be zero until allthe storage capacity has been completely filled, and thereafter there are no restrictions to flow through the outlet.

Option 2. Reduce the amplitude of the runoff hydrograph in direct proportion to the reduction in runoff volume

This option involves multiplying the unadjusted hydrograph ordinates by the ratio of the LID runoff depth to the unadjusted runoff depth, as:

$$q_{adjust} = q_{NoLID}\left(\frac{Q_{LID}}{Q_{NoLID}}\right) \tag{2}$$

where q_{adjust} = ordinate of adjusted runoff hydrograph
q_{NoLID} = ordinate of unadjusted runoff hydrograph
Q_{LID} = total depth of runoff associated with LID
Q_{NoLID} = total unadjusted depth of runoff

This approach is somewhat comparable to the way a Modified Rational Method is used to generate triangular runoff hydrographs (although that approach assumes a storm of uniform intensity). If the runoff volume is accounted for solely through changes in land cover but the time concentration does not change, the height of the hydrograph is reduced proportionately but the base is not.

Option 3. Subtract retention from rainfall

Letting R represent the total retention volume divided by total drainage area, the calculation of runoff using this approach can be formulated as follows:

$$Q = \frac{(P - I_a - R)^2}{(P - I_a - R) + S} \tag{3}$$

Subsequently, the analyst can perform the usual unit hydrograph calculations.

Option 4. Subtract retention from runoff

Subtracting retention from the depth of runoff generated by the land surface can account for the retention explicitly, as expressed by this formula:

$$Q = \frac{(P - I_a)^2}{(P - I_a) + S} - R \tag{4}$$

Executing this option involves subtracting the retention volume from the leading edge of the excess rainfall hyetograph before the convolution calculations are performed.

Option 5. Adjust CN for 24-hour storm depth

A standard assumption given in TR-20 is that $I_a = 0.2S$. Consequently, the NRCS standard runoff equation is sometimes expressed as

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S} \tag{5}$$

Subtracting the total retention from the total runoff at the end of a storm event gives a runoff value that a different S value can be based on. The equation

$$Q - R = \frac{(P - 0.2S)^2}{P + 0.8S} \tag{6}$$

can be solved for a revised value of S, which will increase with increases in retention, and then a revised CN value can be calculated from the revised S. That revised CN can subsequently be used to generate a new runoff hydrograph.

RESULTS

For each of the options considered, a family of curves was generated to illustrate the expected reduction in peak flow corresponding to different amounts of storage provided on site. An example of one such family of curves is shown in Figure 1.

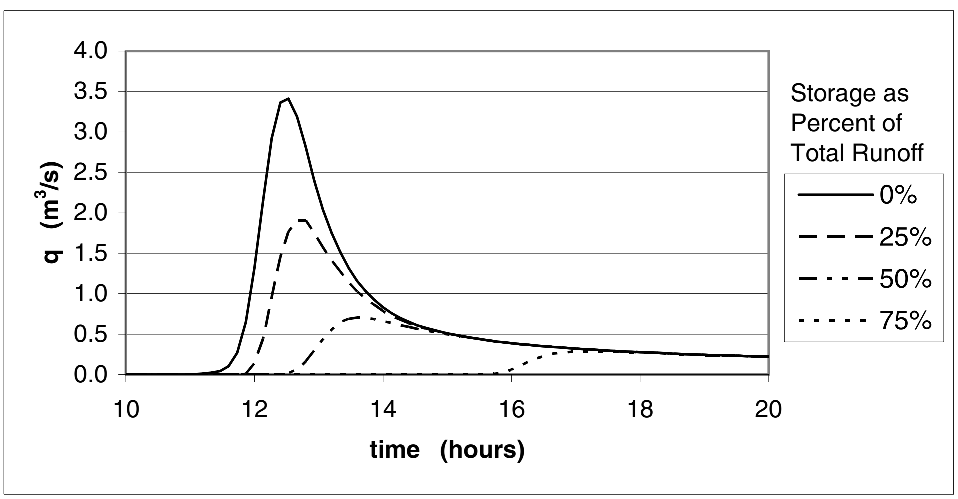

Figure 1. Changes in runoff hydrograph associated with Option 4.

It was also of interest to determine how the amount of retention storage needed to reduce the peak flow to a given level compared with the estimated volume of a detention pond that would otherwise be required to achieve the same level. For several peak flow reduction values, the detention pond volume was estimated simply by extending a line segment from the leading edge of the hydrograph to the target peak value on the recession limb of the hydrograph, and subsequently obtaining the area of the hydrograph above the line segment.

Predicted reductions in peak flow were compared among all the storage options. A comparison based on one selected set of hydrologic parameters is shown in Figure 2.

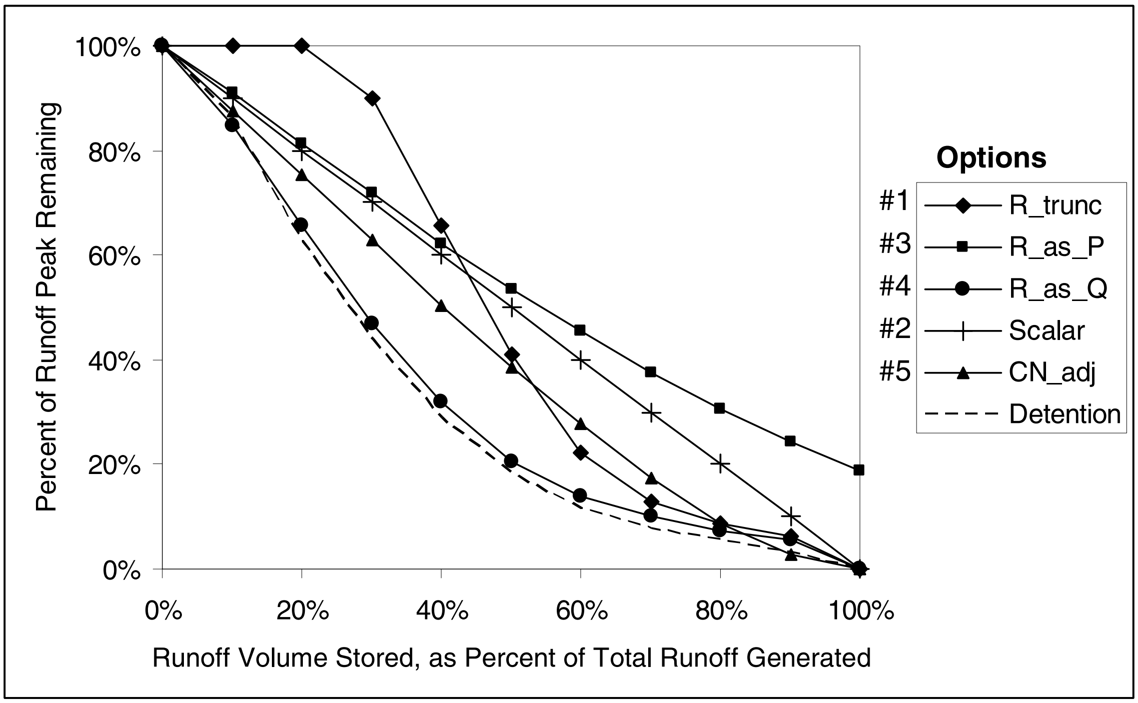

Figure 2. Comparison of different methods of accounting for runoff storage. (CN = 75, Tc=1 hr, D.A. = 1 km^2)

DISCUSSION

The Five Options Compared

Option 1. Because truncating the runoff hydrograph results in a vertical ascending limb, this approach predicts no reduction of the peak flow until the volume of retention storage exceeds the volume of the hydrograph to the left of the unadjusted peak. In actuality, the distribution of retention features within a drainage area, and the actual routing of runoff through them once they are filled to capacity, would be expected to reduce the slope of the ascending limb of the hydrograph considerably.

Option 2. The shape of the curve in Figure 2 is perfectly linear. Relative to options 1, 4, and 5, this approach predicts larger peaks when 50% or more of the runoff is stored.

Option 3. Using this approach, the volume of retention provided will not be fully accounted for. Just as runoff is always less than rainfall when the standard NRCS runoff formula is used, this calculation will generate a change in runoff volume that is always less than the volume of retention actually provided.

Option 4. Accounting for the runoff volume as described in Option 4 predicts in the least amount of runoff for all but the highest levels of peak runoff reduction. The relationship between peak flow and storage volume is nearly identical to that for detention storage.

Option 5. The *CN* adjustment method will produce a different *CN* value depending on the depth of precipitation used, even if the land cover, soil characteristics, antecedent moisture conditions and the amount of added retention remain the same. As a rule, for levels of precipitation that are below the level on which the *CN* adjustment is based, this approach will underestimate the availability of storage. Above the precipitation level on which the *CN* adjustment is based, this approach will overestimate the availability of storage.

Figure 3 shows a comparison of depth calculations for Options 3 ("P minus R"), 4 ("Q minus R), and 5 ("CN Adjustment"). Relative to the standard runoff curve, Option 3 moves the runoff curve to the right, and Option 4 moves it downward. The curve drawn using Option 5 starts somewhat to the right of the standard curve, and ends where the difference in runoff is equal to the total depth of retention.

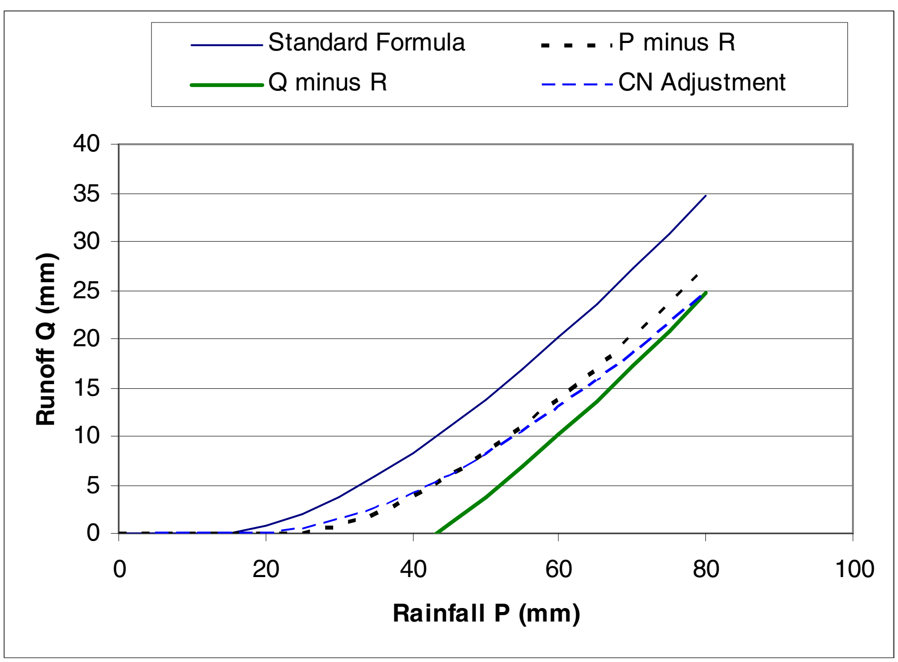

Figure 3. Comparison of depth of runoff calculations.
(CN = 80; overall retention depth = 10 mm)

Figure 3 illustrates the particular case in which a runoff curve has been drawn based on a *CN* that was adjusted using Equation 6 for a rainfall depth of 80 mm and a retention depth of 10 mm. The adjusted curve gives a runoff value of approximately 13 mm for 60 mm of rainfall. However, if a *CN* is recalculated using Equation 6 for a rainfall depth of 60 mm, the amount of runoff is approximately 10 mm (which is only coincidentally equal to the amount of storage). But since the accumulation of precipitation from 0 to 80 mm necessarily passes through the value of 60 mm, it seems reasonable to expect that the runoff depth associated with 60 mm should be exactly the same for the same land use and soil type, regardless of whether a given storm happens to contribute additional rainfall beyond the 60 mm.

PROJECT OUTCOME

Subtracting the aggregate retention depth from the runoff depth (Option 4) was ultimately selected as the approach to hydrologic analysis that would be implemented in a spreadsheet. A thumbnail graphic of the spreadsheet resulting from this effort is shown in Figure 4. The three-page format is designed to make these calculations easy to present and review when incorporated into formally submitted stormwater management plans. The spreadsheet has been dubbed the "LID Quicksheet".

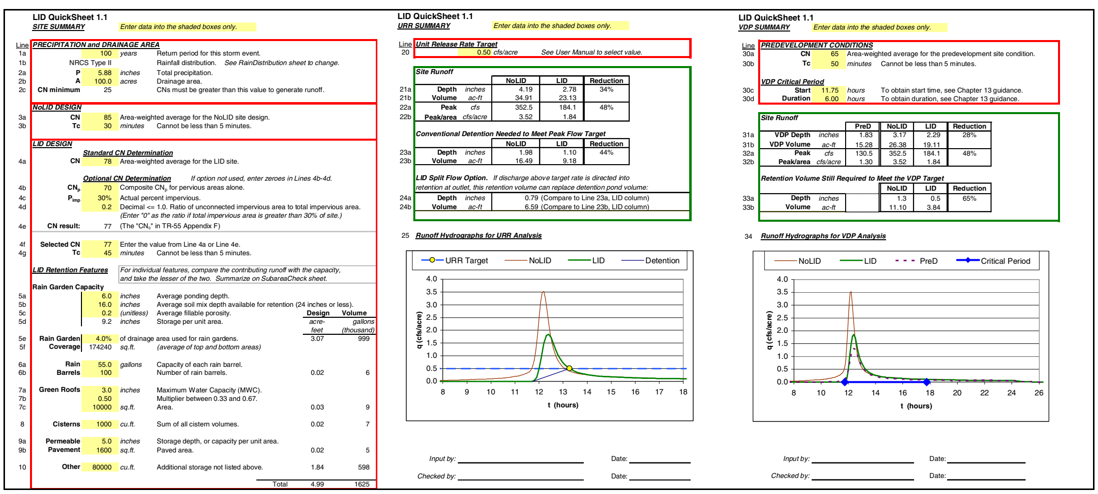

Figure 4. Thumbnail graphic of themain user interface for the LID Quicksheet.

On the first page, the user provides input values common to the URR and VDP. Primary variables for the input page include the precipitation depth and drainage area along with *CN* and *Tc* values. The user can also input parameters associated with calculating the retention capacity of various on-site LID features, such as rain gardens, permeable pavement and green roofs. The capacity of storage devices not specifically listed can be added as well.

The second page provides input cells and output values pertaining specifically to the URR. The output shows how LID site characteristics affect the runoff volume and peak flow, as well as the detention pond capacity (if any) still needed to fully control the peak flow after on-site retention features have been provided.

The third page provides input cells and output values pertaining specifically to the VDP. And if the user wishes to do so, this page can be used to compare the volume and peak of the entire LID runoff hydrograph with the volume and peak of the entire predevelopment hydrograph. An example of the hydrograph comparison chart provided on this page is shown in Figure 5.

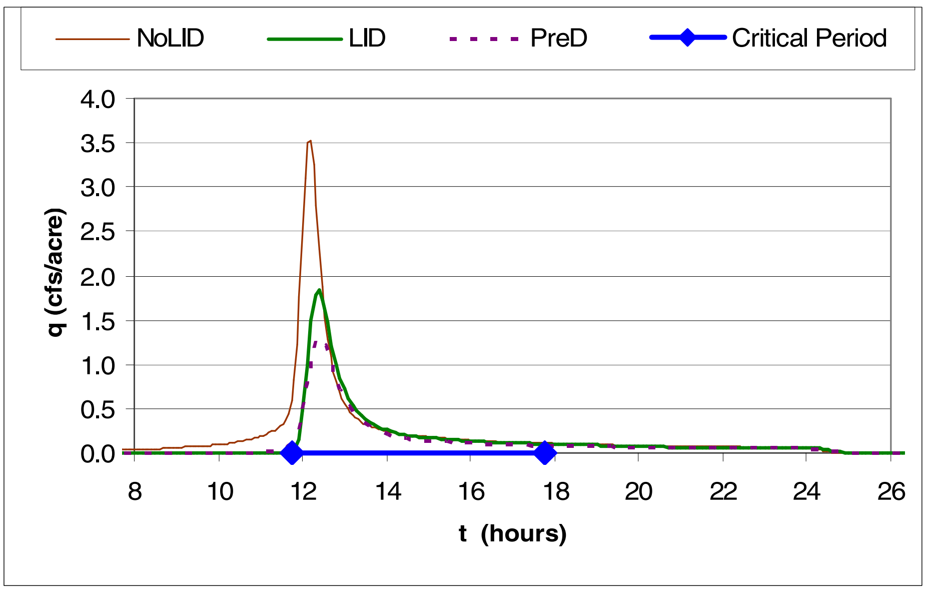

Figure 5. Hydrograph comparisons for the Volumetric Design Procedure.

The accompanying user guide provides line by lineinstructions for each input value, along with an explanation of each output value. A particularly important instruction advises users to evaluate each retention feature on the site of interest to determine whether it will be filled to capacity during the design storm event. If the volume of runoff flowing into the retention feature is less than its full capacity, then that volume of runoff, rather than the capacity of that feature, should be used as the amount that affects the runoff hydrograph for the site.

As this manuscript was being finalized in early 2005, the MMSD was anticipating incorporation of the LID Quicksheet and user guidelines into the District's stormwater management guidance. Prior review by a number ofcommunity stakeholder groups has been favorable. Initial applications of this tool after it has been approved will provide valuable practical feedback.

CONCLUSIONS

The standard NRCS method for calculating runoff hydrographs can be adapted for low-impact development by aggregating the total runoff volume retained across a drainage area and evaluating it as a runoff depth that must be exceeded during a storm event before any runoff leaves the drainage area. This adaptation is among the more technically defensible alternatives compared in this study and is especially suited where all site runoff is directed through a number of similarly sized and distributed on-site stormwater retention features. This approach may also be the one most likely to encourage low-impact development because it tends to predict the greatest reductions in the peak flow for a given retention volume.

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